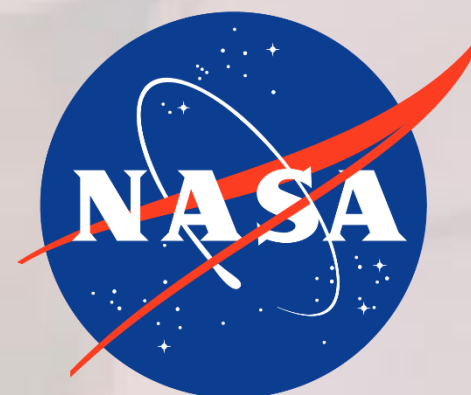


Feasibility of Passive Cryogenic Cooling for Solar Powered Outer Planetary Missions

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Topics

- Cryogenic Cooling Needs
- Cryogenic Passive Cooling
- Survey of Solar Powered Planetary Missions
 - Rosetta, Dawn and Juno Missions
- Solar Array Technology and Needs for Outer Planetary Missions
- NASA's Planned Europa Clipper Mission
- Future Use of Solar Power for Space Application
- Active Cooling Systems
- Summary

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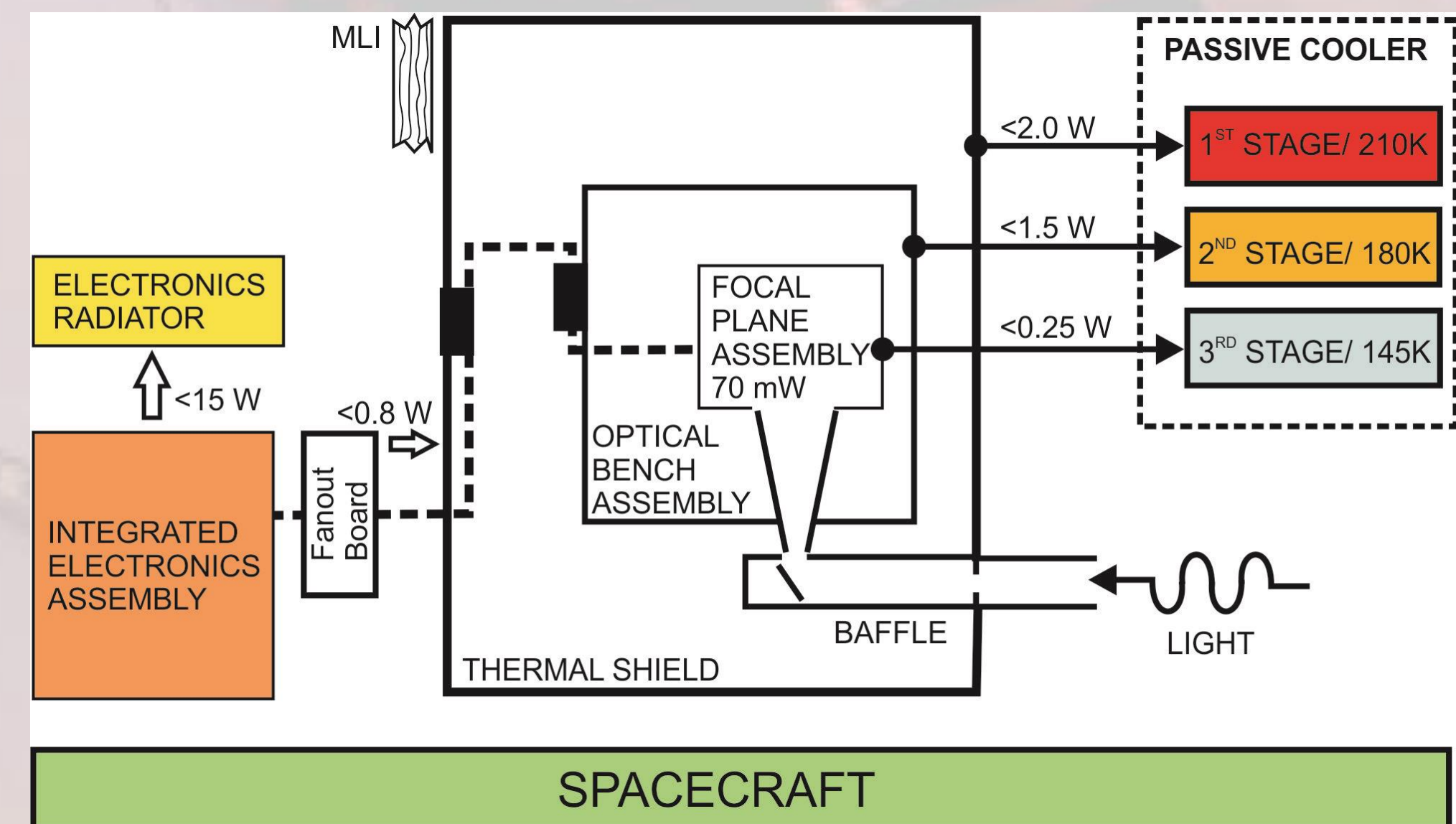
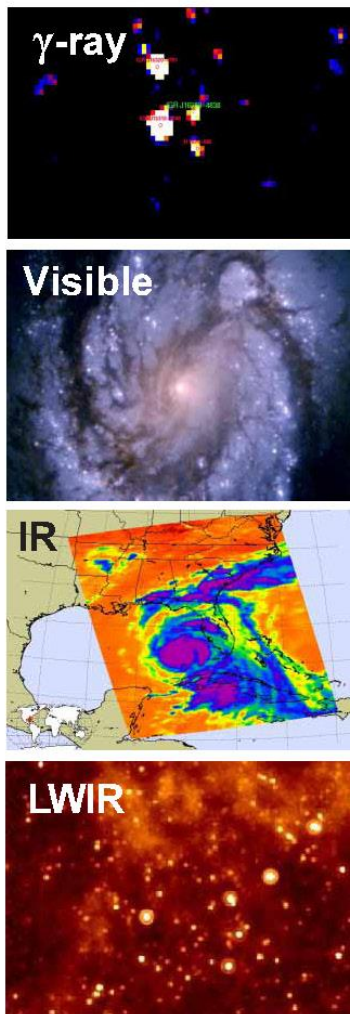
Cryogenic Cooling Needs

- Low cryogenic temperatures are needed
 - Detector sensitivity increases with decreasing temperature
 - Low optics temperatures reduce background photon noise
 - Increasing detector spectral range to far infrared requires lower temperatures
- Larger format detectors with higher refresh rates increases power dissipation
- Passive cooling is preferred over active cooling to provide cryogenic cooling to instruments
 - Lower detector temperatures with increasing power dissipations becomes increasingly difficult because of Stefan-Boltzmann law
 - Passive cooler designer must focus on reducing internal parasitic and external environmental heat loads in addition to maximizing radiator view to cold space
- Large solar arrays required for outer planetary missions along with spacecraft pointing attitude requirements near the target planetary bodies poses significant challenge for passive cooling

Cryogenic Cooling

- Types and wavelengths of electromagnetic radiation, the blackbody temperature with peak emission at the wavelength, and applicable detector types and their required operating temperature
- Typical thermal schematic for cryogenically cooled spectrometer: cryogenic staging within instrument minimizes heat load requirements on the 3rd-stage passive cooler
- Need to carry suitable design margins on heat loads
 - JPL design principles follows Aerospace Corp. guidelines in AIAA-1991-1426-764 paper
 - Recommends 40-50% margins in phase A/B

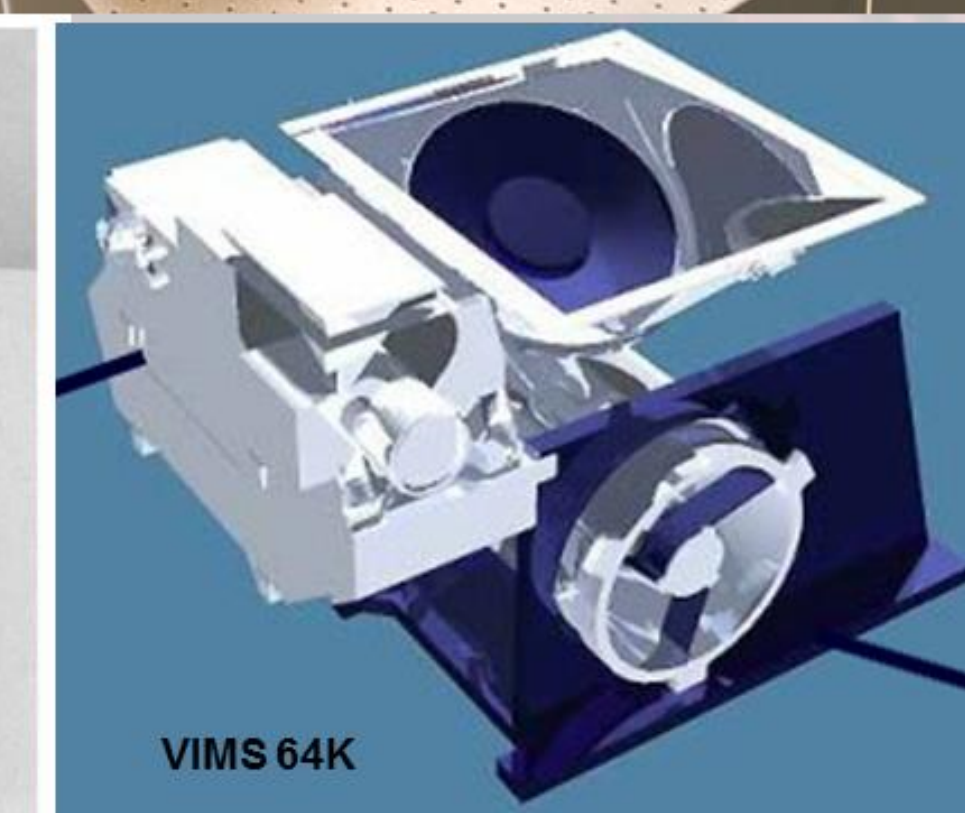
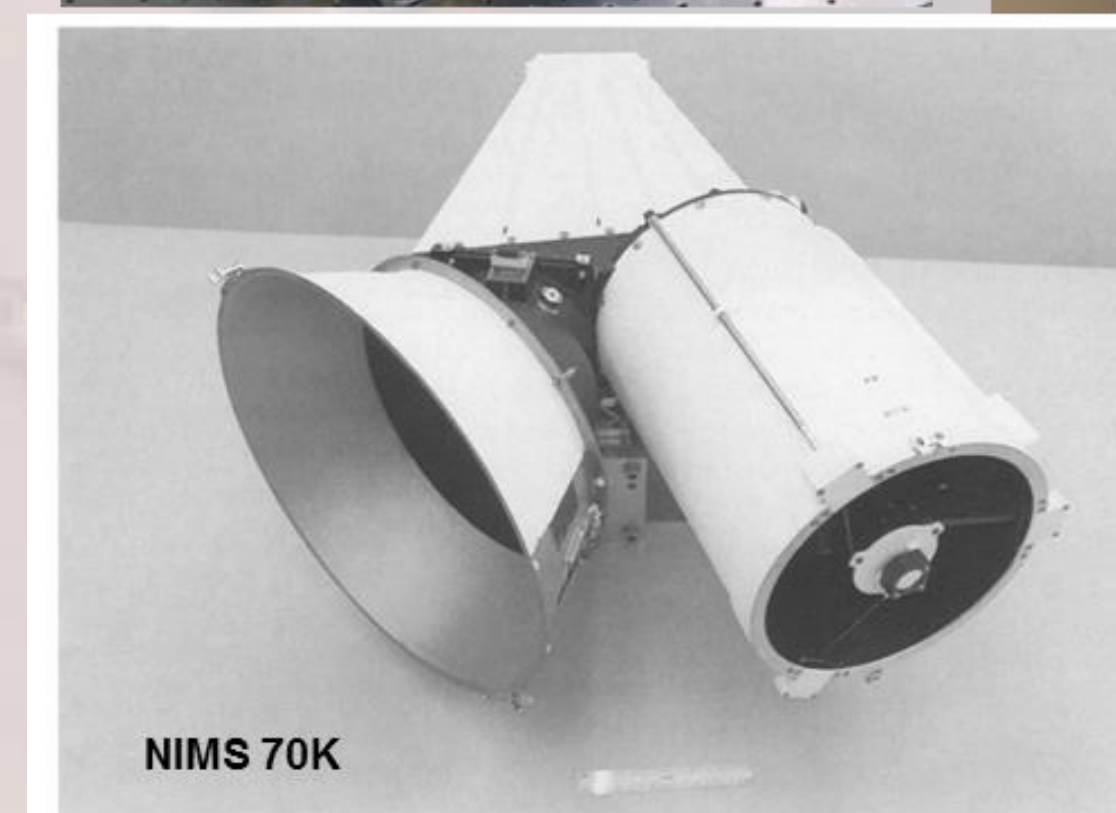
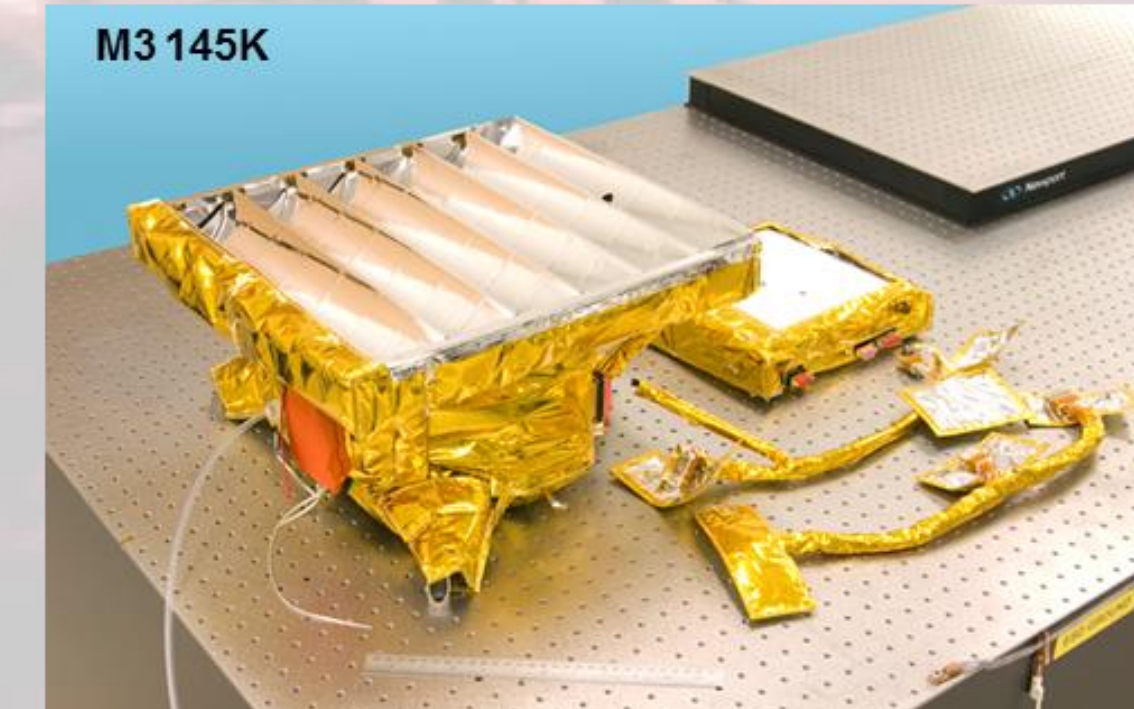
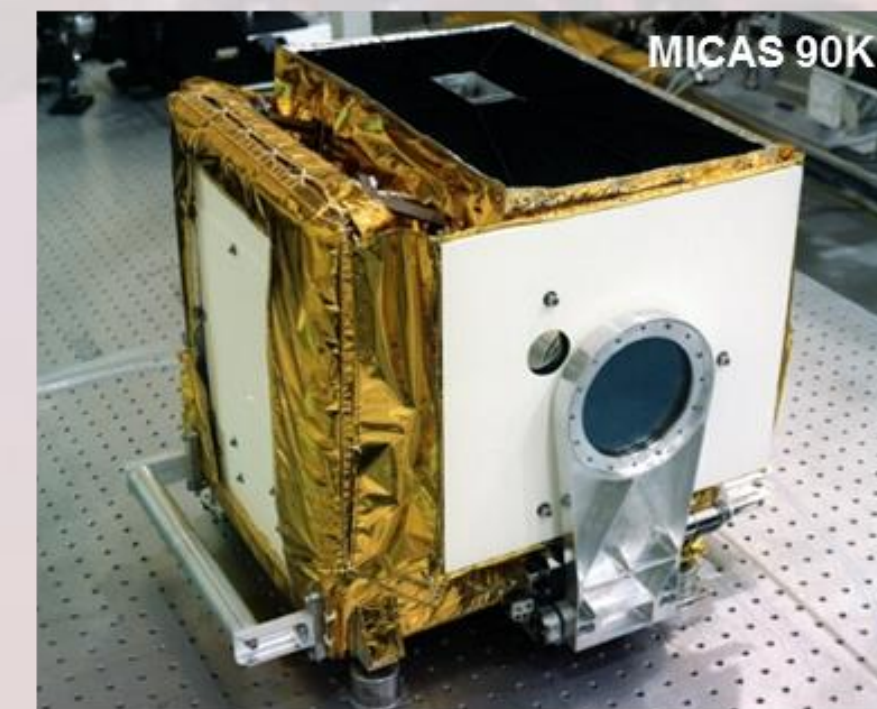
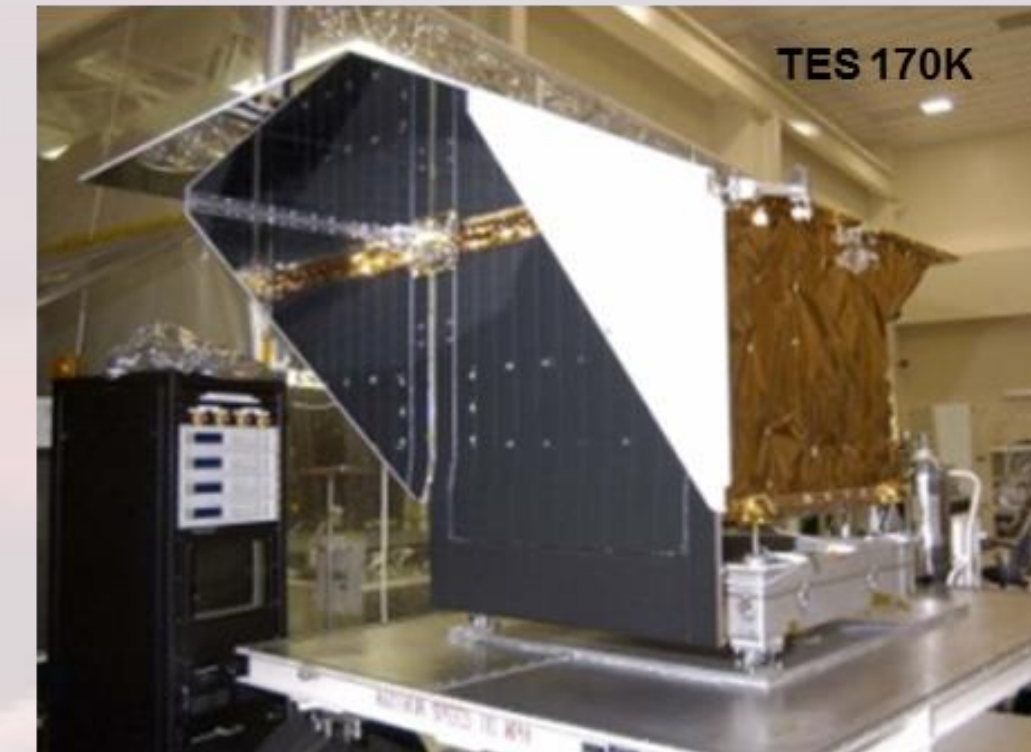
Radiation Type	Wavelength (microns)	Blackbody Temp. (K)	Detector Technology	Detector Temp. (K)
γ -rays	10^{-5}	3×10^8 K	Ge Diodes	80 K
γ -rays	10^{-4}	3×10^7 K	Ge Diodes	80 K
x-rays	10^{-3}	3×10^6 K	micro	0.05 K
x-rays	10^{-2}	3×10^5 K	calorimeters	0.05 K
UV	0.1	30,000 K	CCD/CMOS	200-300 K
visible	1	3000 K	CCD/CMOS	200-300 K
IR	2	1500 K	HgCdTe	80-130 K
IR	5	600 K	HgCdTe	80-120 K
LWIR	10	300 K	HgCdTe	35-80 K
LWIR	15	200 K	HgCdTe	35-60 K
LWIR	20	150 K	Si:As	7-10 K
LWIR	50	60 K	Ge:Ga	2 K
LWIR/ μ waves	100	30 K	Ge:Ga	1.5 K
microwaves	200	15 K	Bolometers	0.1 K
microwaves	500	6 K	Bolometers	0.1 K



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Passively Cooled Cryogenic Instruments

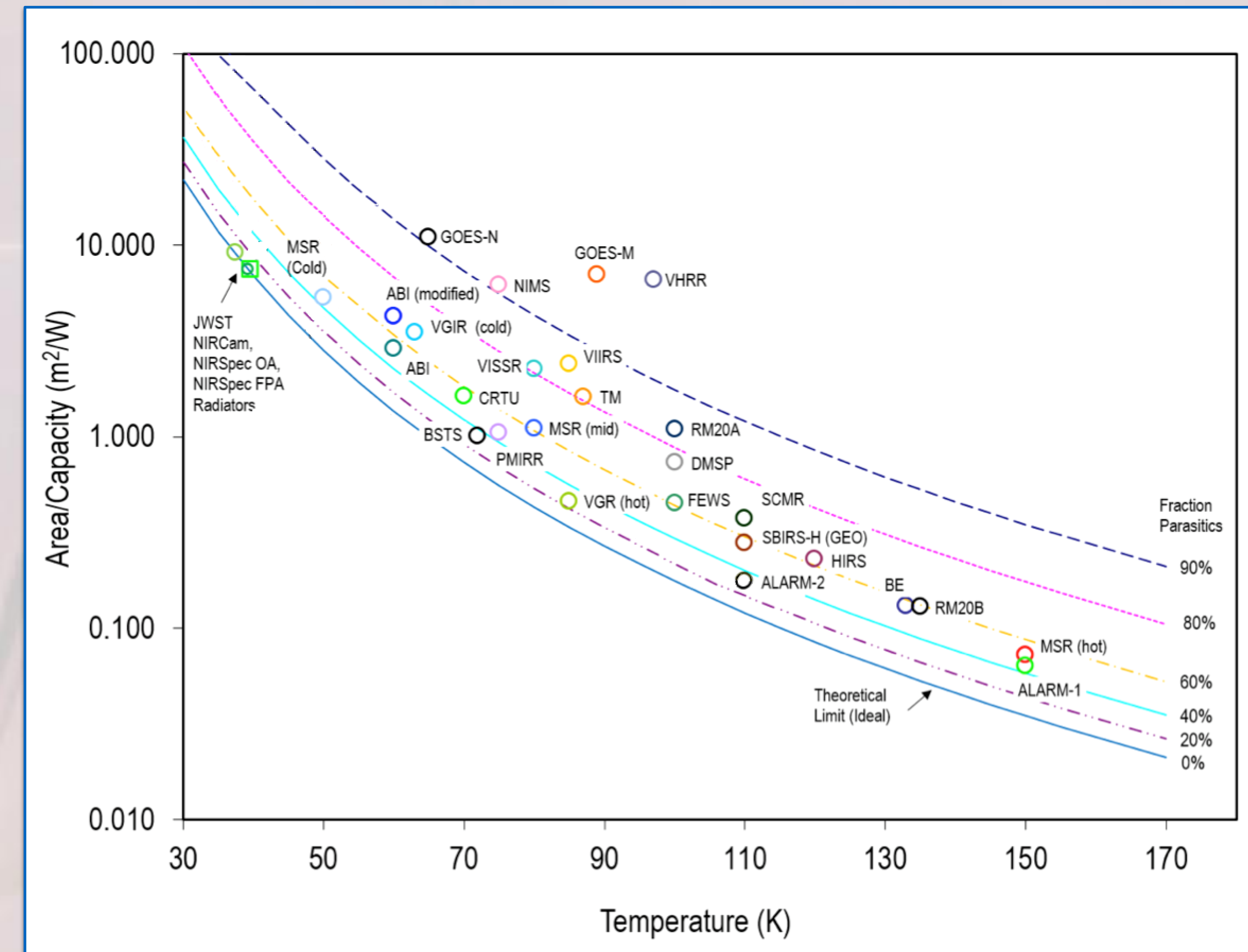
- JPL flight instruments with cryogenic passive coolers with various configurations showing low-emissivity shields
- These instruments have demonstrated successful long-term performance in excess of 10 years from LEO, and Moon orbit to outer planetary missions



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Passively Cooled Cryogenic Instruments (Cont'd)

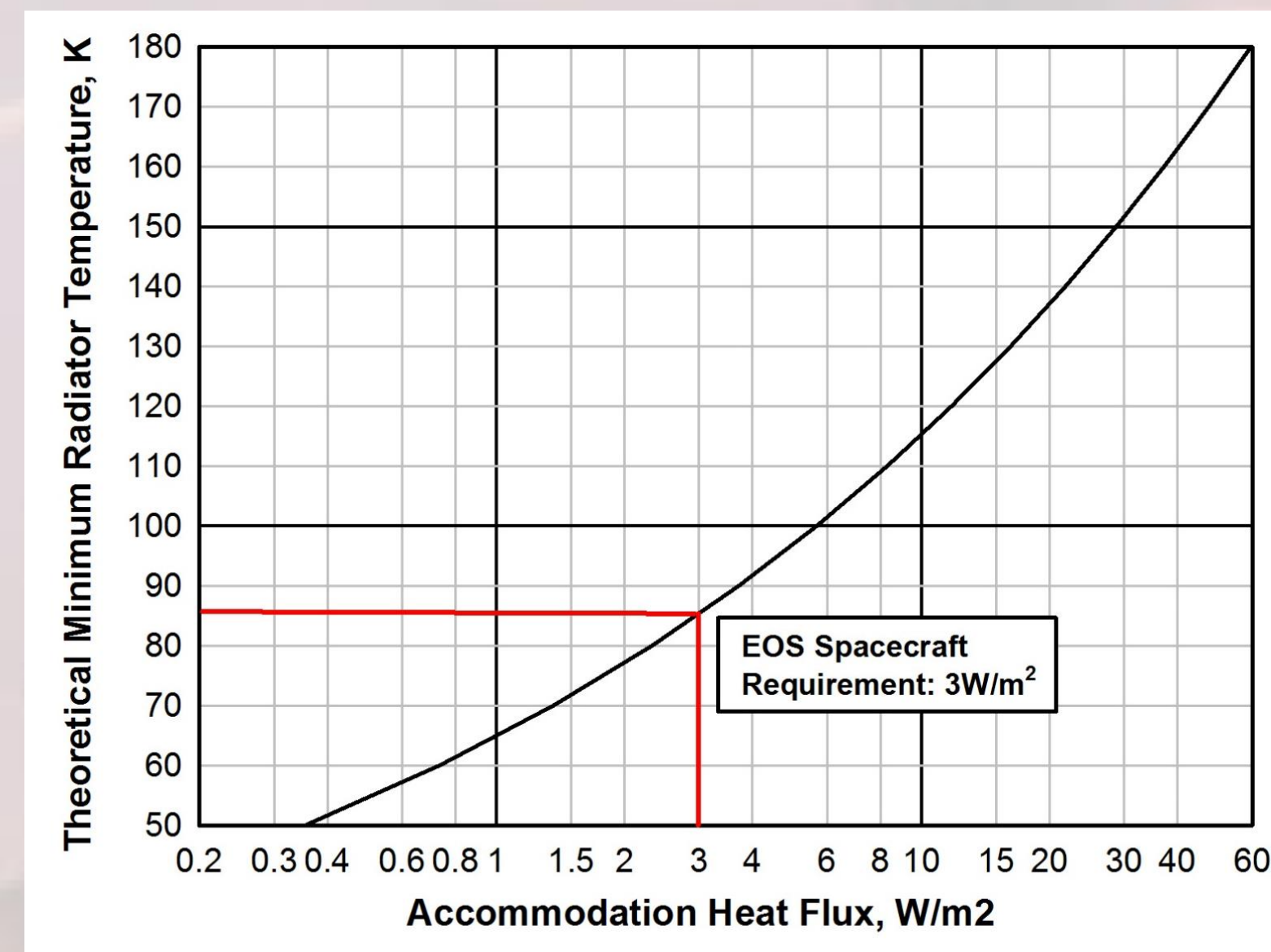
- Performance of heritage passive coolers
- Comparison of area divided by heat load (excluding parasitic loads) vs. temperature
- Moving upwards at a fixed temperature, increased fractional parasitic heat load or reduced emittance causes performance to be reduced compared to an ideal radiator
- For a fixed radiator design, increased heat load results in higher temperature and a reduction in the fraction of parasitic heat load
- More challenging performance is represented by points at lower temperatures or points that are closer to the theoretical limit



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Single-Wing Spacecraft in Sun-Synchronous Orbits

- NASA's Earth Observing System (EOS) Spacecraft: Terra, Aqua and Aura spacecraft with large single-wing solar arrays
- EOS spacecraft are in sun-synchronous orbits at 705 km altitude with ideal accommodations for passive cooling
- Passive cooler theoretical minimum radiator temperature as a function of spacecraft accommodation heat flux
- NASA's EOS used a spacecraft accommodation requirement of $< 3 \text{ W/m}^2$
- Passive cooler performance both in terms of radiant capability and/or temperature is often limited by the presence of radiant sources within the cooler radiator surfaces field of view
- Spacecraft with large solar arrays pose a significant challenge for passive cooler designers with obscured clear field of view to cold space and additional solar and/or infrared heat loads requirements



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Outer Planetary Missions

S/C	Mission	SA Power, Specific Power, SA Temp	Solar Array size/ Configuration	SEP	Launch and Arrival Dates	Mission Lifetime
Rosetta	Comet Orbiter Lander	7.1 kW at 1 AU 850 W at 3.4 AU 400 W at 5.25 AU and 143 K ~50 W/kg at 1 AU	64 m ² solar array area Two 2.25m x 14m wings 32 m tip-to-tip +/- 180 deg rotation	No	Mar 2004 to Sept 2016	12 years
Dawn	Protoplanet Orbiter Vesta/ Ceres	10.3 kW at 1 AU 1.3 kW at 3 AU, 185 K ~80 W/kg at 1 AU	36.4 m ² solar array area Two 2.2 m x 8 m wings 19.7 m tip-to-tip	Yes	Launch:9/27/2007 Vesta:7/16/2011 Ceres: 3/6/2015	Primary: June 2016 Extended: June 2017 (~10 yrs)
Juno	Jupiter Orbiter	14 kW at 1 AU 500 W at Jupiter ~50 W/kg at 1 AU	65.5 m ² solar array area Two 24.0 m ² and one 17.5 m ² wings, Fixed wings at 120deg apart	No	Aug 2011 to Feb 2018	Farthest solar power S/C from Earth (6 yrs)

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Rosetta Mission

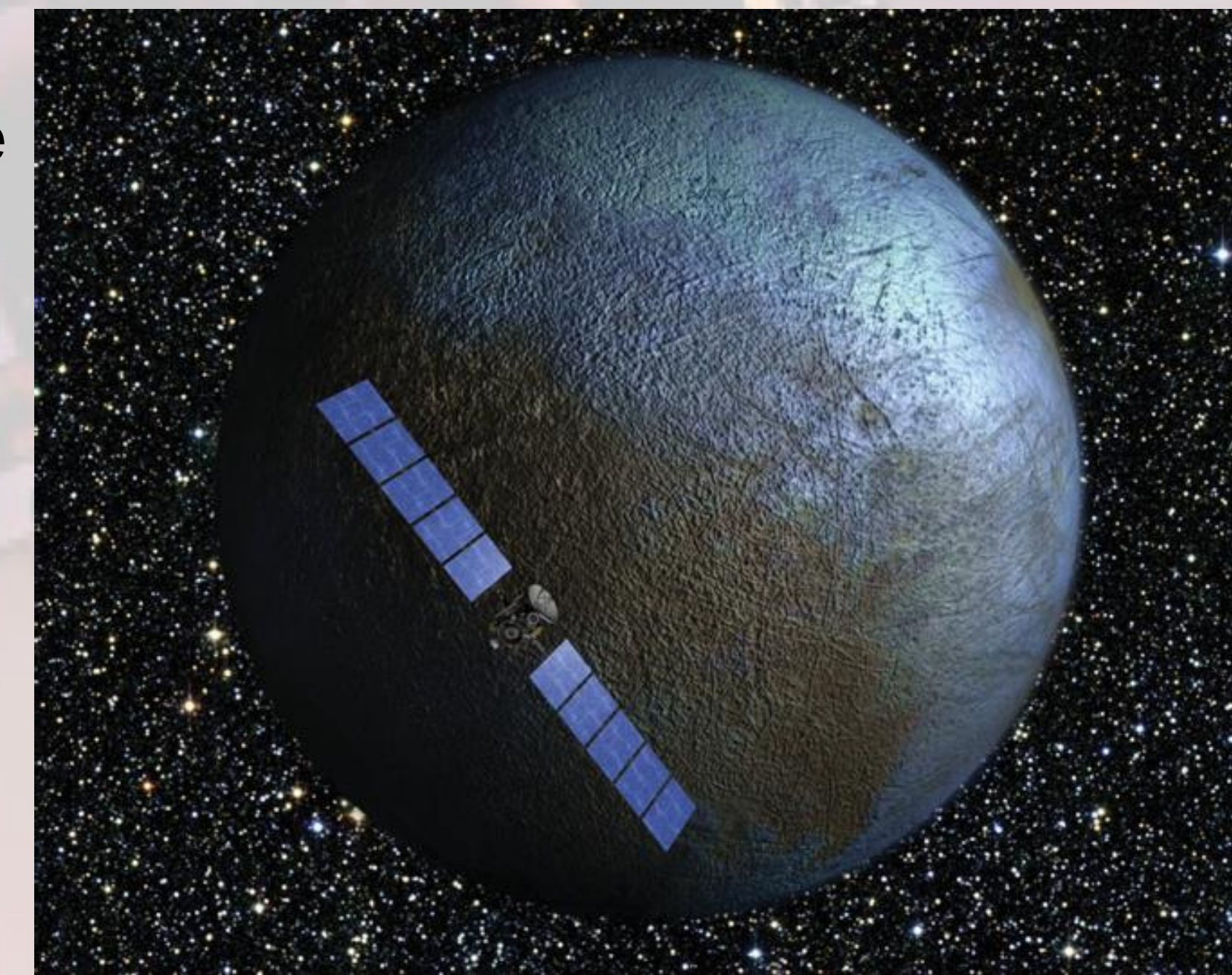
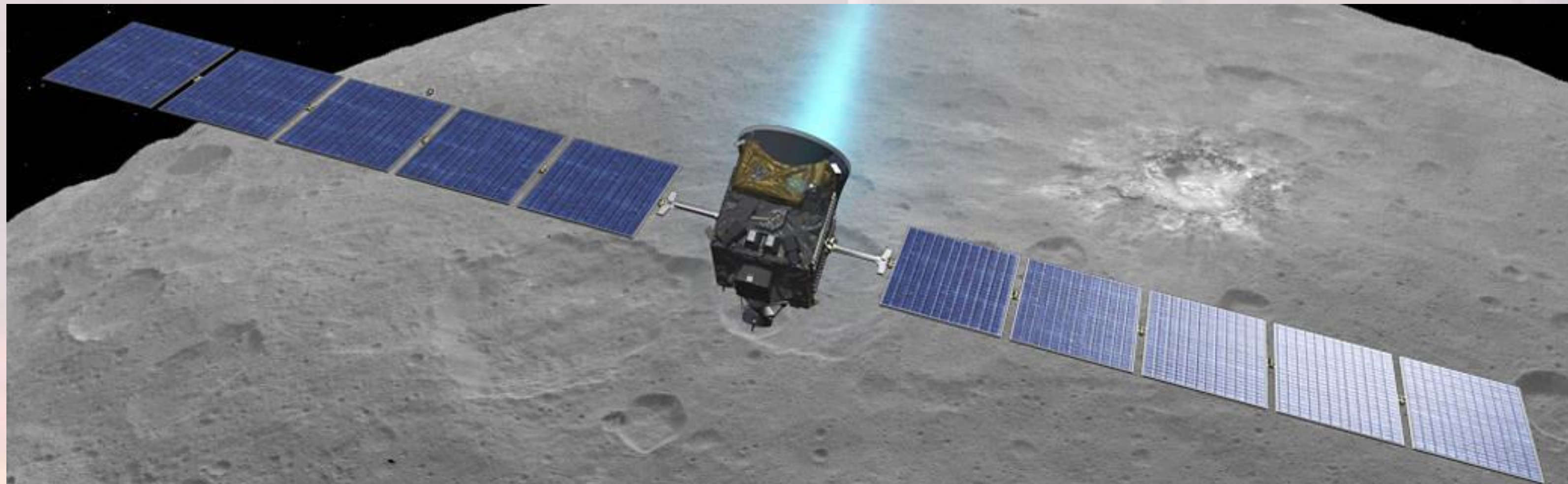
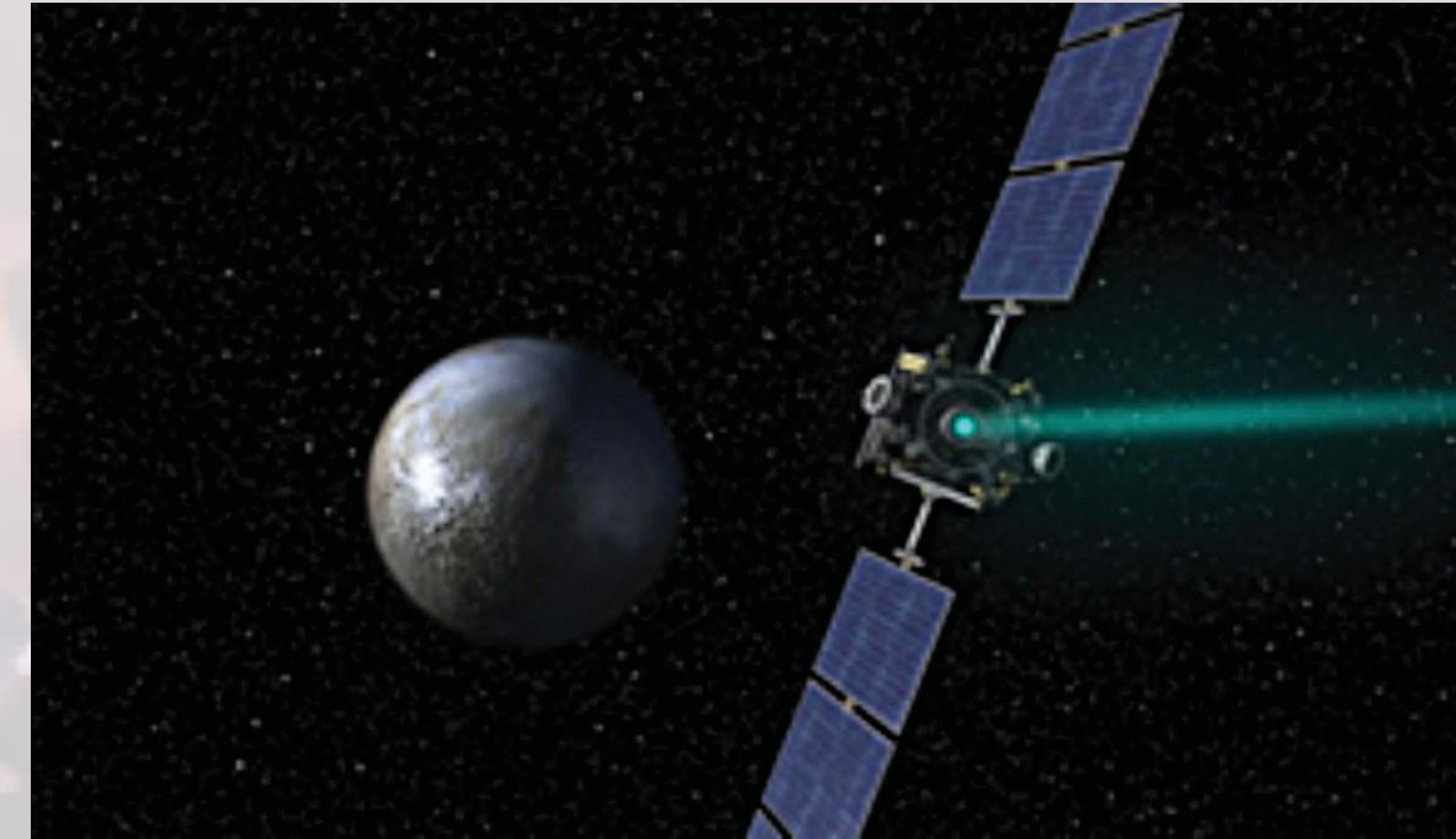
- Rosetta spacecraft with two-wing rotating solar arrays and Philae lander at comet 67P/Churyumov-Gerasimenko
- The large two-wing configuration on the Rosetta spacecraft and complex maneuvering produces thermally changing environment and makes it impractical to provide cryogenic passive cooling
- The Visible Infrared Thermal Imaging Spectrometer (VIRTIS) on Rosetta was primary science payload and required cryogenic cooling of the focal plane
 - The visible channel charge coupled device (CCD) covers the spectral range of 0.25 to 1 μm and along with spectrometer were cooled passively to 130 K
 - The two infrared channels with coverage of 1 to 5 μm and 1.9 to 5 μm were actively cooled to 70 K with one cryocooler each
 - Both infrared channels use mercury cadmium telluride (HgCdTe) focal planes



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Dawn Mission

- Dawn spacecraft arrived at Ceres on March 2015
- Two-wing solar array configuration on this spacecraft along with the environments make it difficult to accommodate a passive cryogenic cooler
- The Visual and InfraRed (VIR) Spectrometer provided by the Italian Space Agency (ASI) uses a cryocooler to cool its HgCdTe infrared detector to 70 K and the visible CCD detector and spectrometer are passively cooled to 130 K
 - The VIR spectrometer visible channel covers the range of 0.25 to 1.05 μm and the infrared channel 1 to 5.0 μm
 - The VIR instrument is a re-build of the mapping channel of Rosetta VIRTIS spectrometer and the optical concept is inherited from the visible channel of the Cassini Visible Infrared Mapping Spectrometer (VIMS-V) developed for the Cassini mission

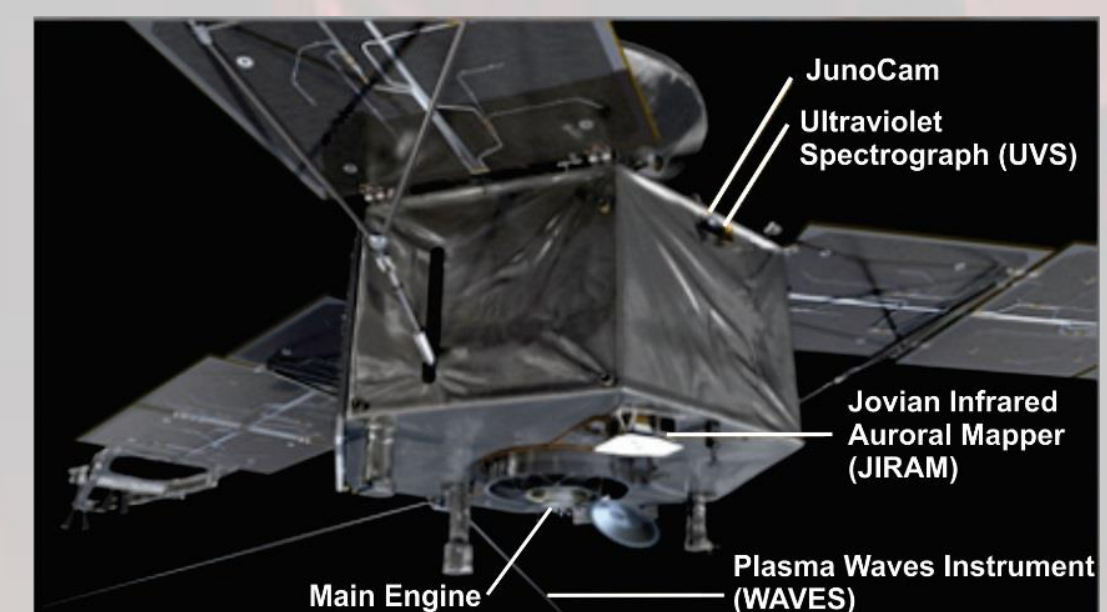


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Juno Mission

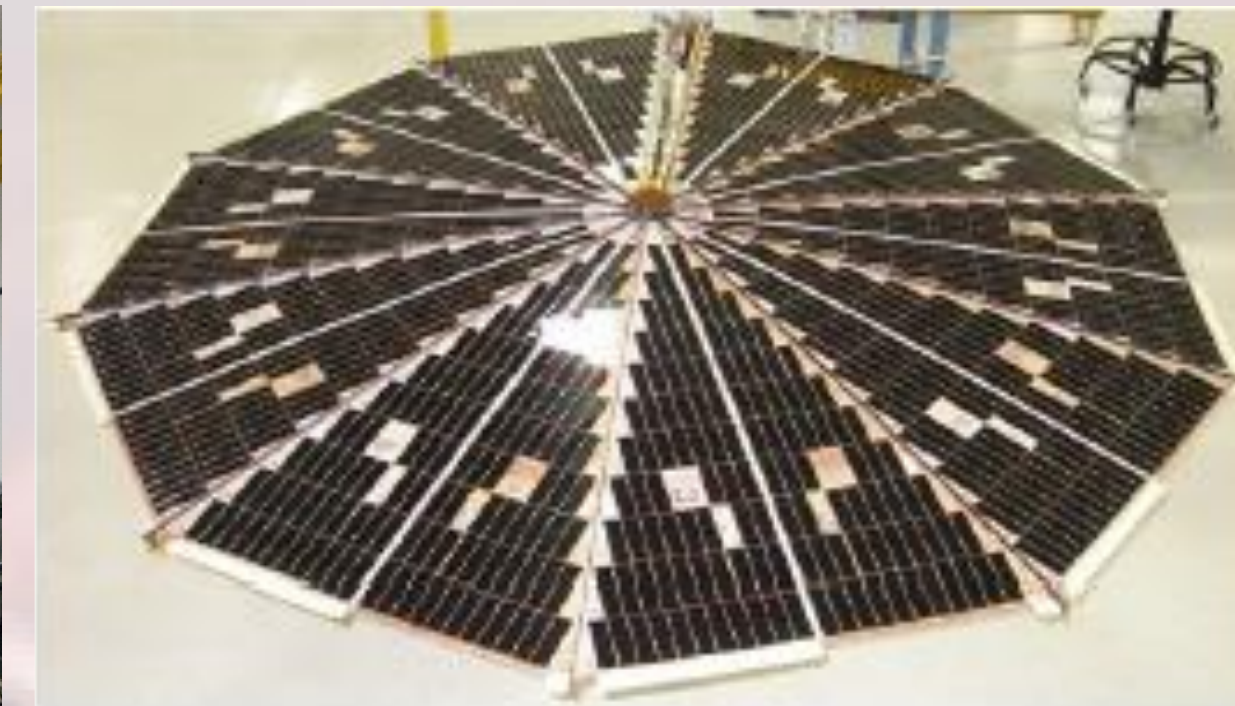
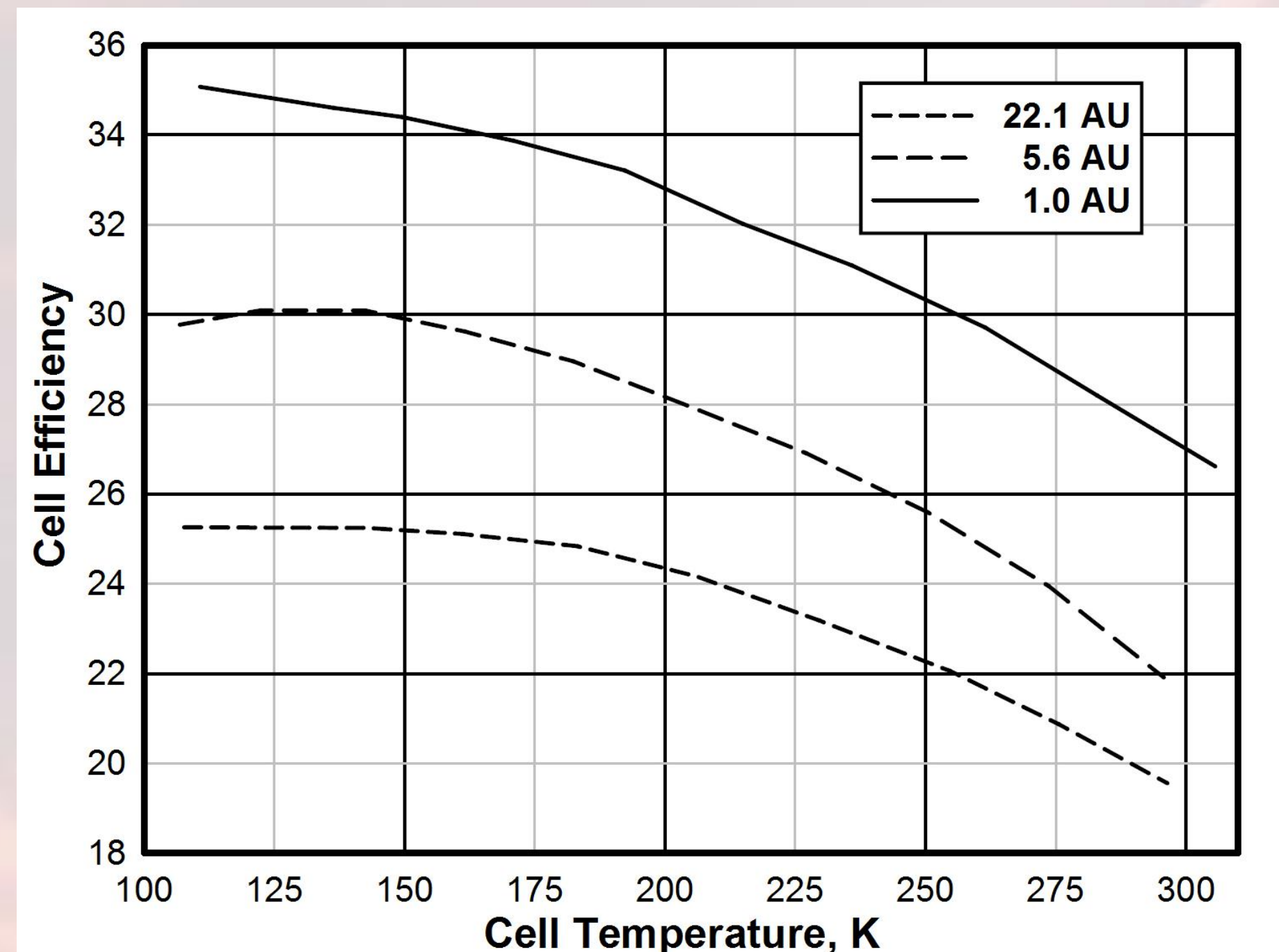
- Juno spacecraft is designed with three large fixed solar arrays
- The JIRAM instrument mounted to the aft deck of the Juno spacecraft views in the same direction as the other optical instruments, UVS and JunoCam
- Two distinct IR focal plane detectors covering a spectral range of 2 to 5 μm using HgCdTe are used for imaging and spectroscopy
 - Both infrared detectors operate at 95 K and the optical head at 130 K
 - Instrument uses 2-stage passive cooler design configuration to provide cooling at 95K and 130K
 - 1st-stage at 130K protects 2nd-stage radiator at 95K with both radiators viewing cold space
- Spacecraft thermal and radiation environments posed significant challenges for JIRAM instrument
 - Passive cooler was accommodated on the same side of the spacecraft with main engine
 - Best possible location for the instrument with relatively good views to cold space
 - Contamination and infrared heat loads from the main engine in addition to infrared planetary heating from Jupiter during the low altitude science acquisition pass is significant challenge
- No known technical papers in the open literature address the thermal design of this instrument
 - Highly elliptical orbits with ~2 hr science data acquisition periods with a relatively high altitude of 4200km and 14 day orbit period provides a benign external thermal environment
 - The short science acquisition duration along with a fairly benign external environment does permit the use of passive cooling to accommodate a passive cryogenic cooler on this spacecraft
- Previous versions of this instrument concept on *Rosetta and Dawn* required 70 K for its infrared focal plane whereas the JIRAM instrument infrared focal plane is only cooled to 95 K

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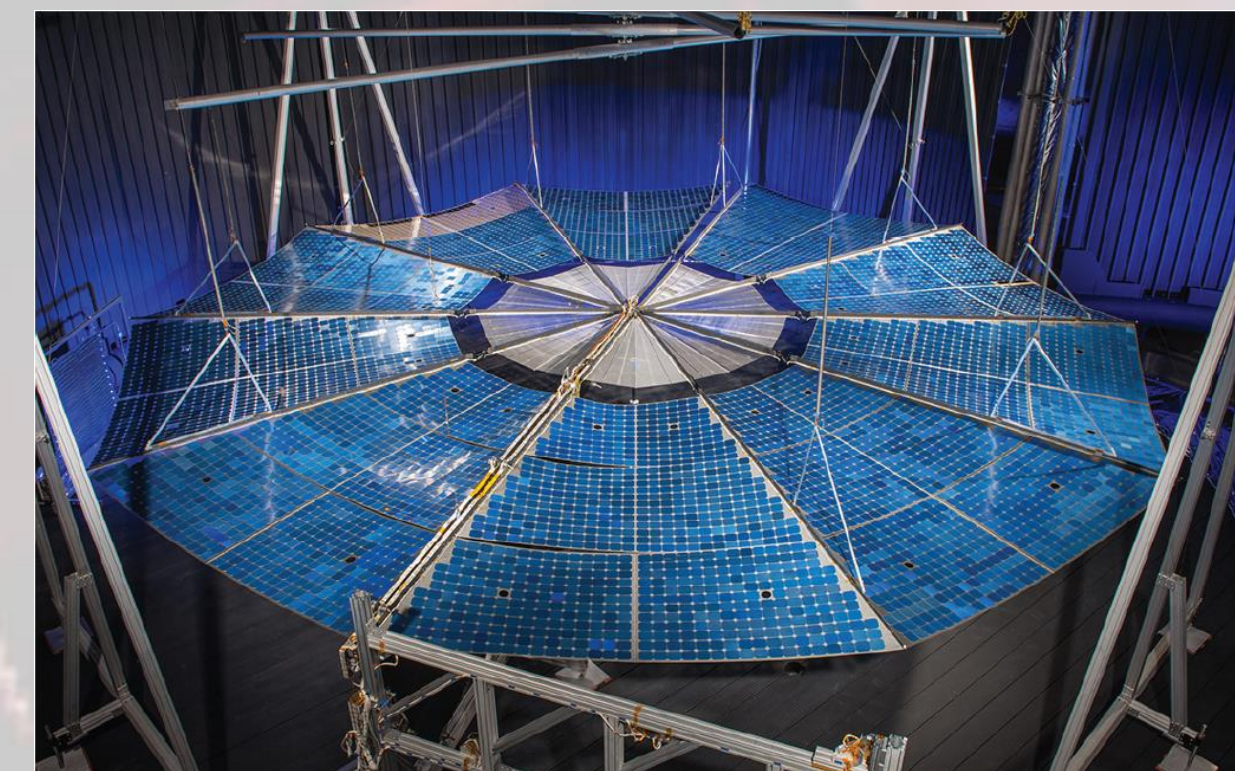


Solar Array Technology

Juno rigid solar arrays wing deployment:
~50-80 W/kg at 1 AU, TRL 9 on Juno (left)
and Dawn (right)



ATK Ultraflex solar array: ~150 W/kg at 1 AU, Ultraflex TRL 9 on Phoenix

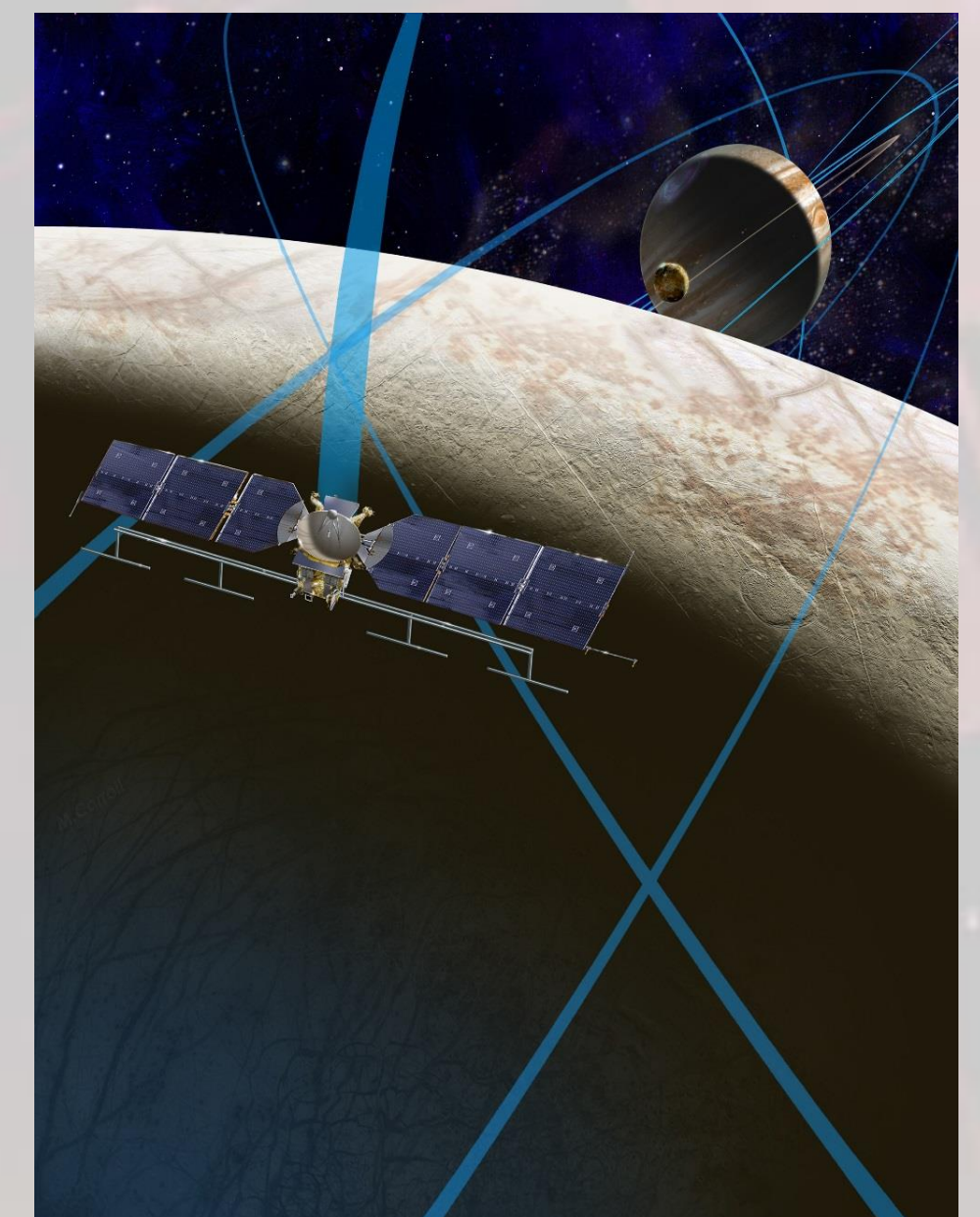
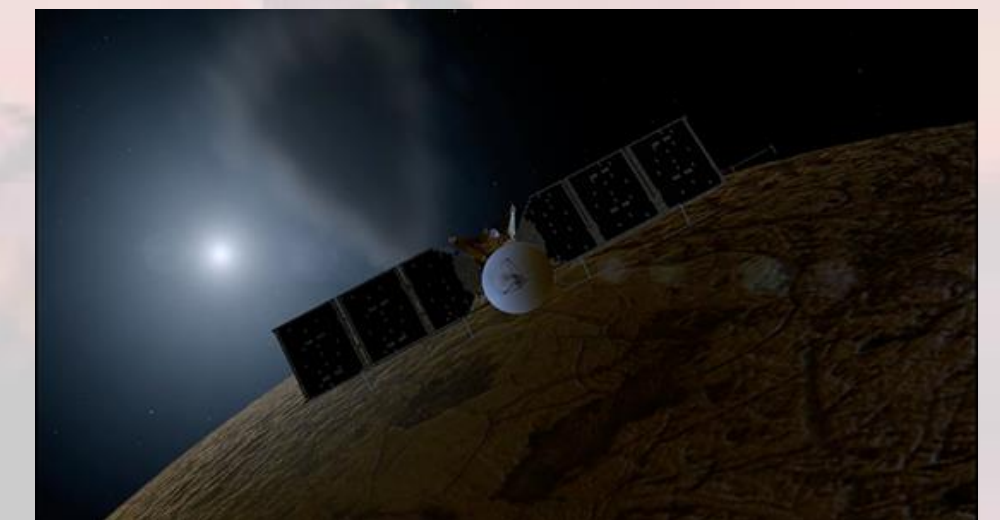
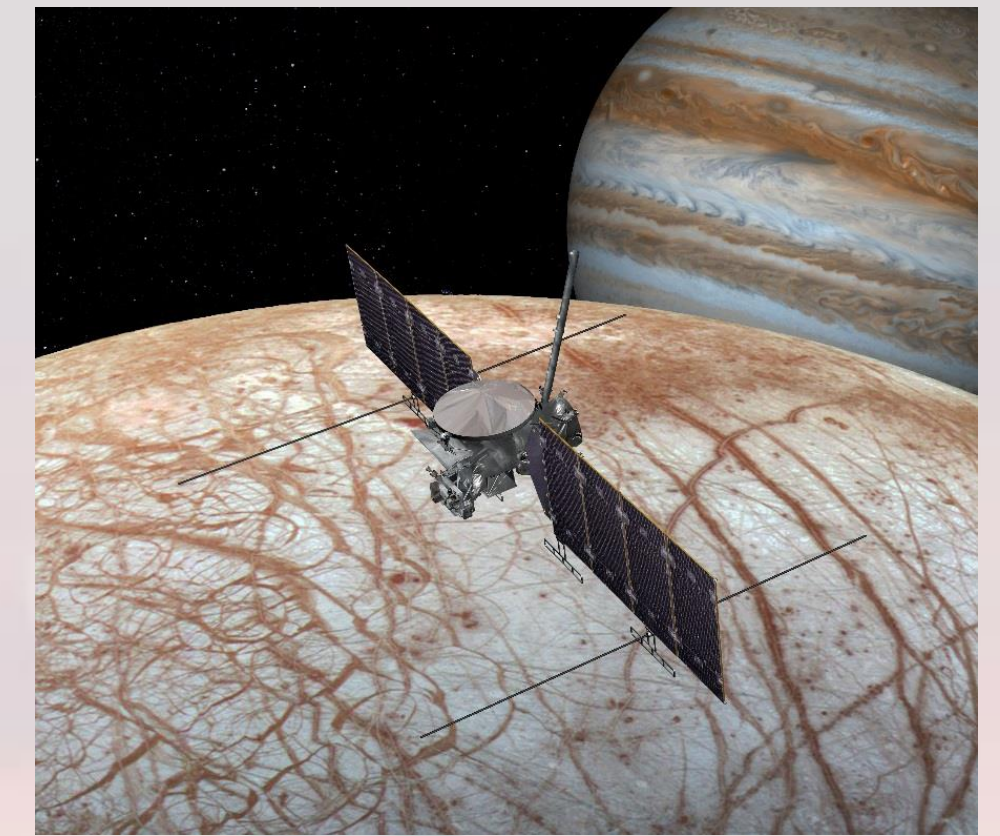


ATK Megaflex, TRL 6

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Planned Europa Clipper Mission

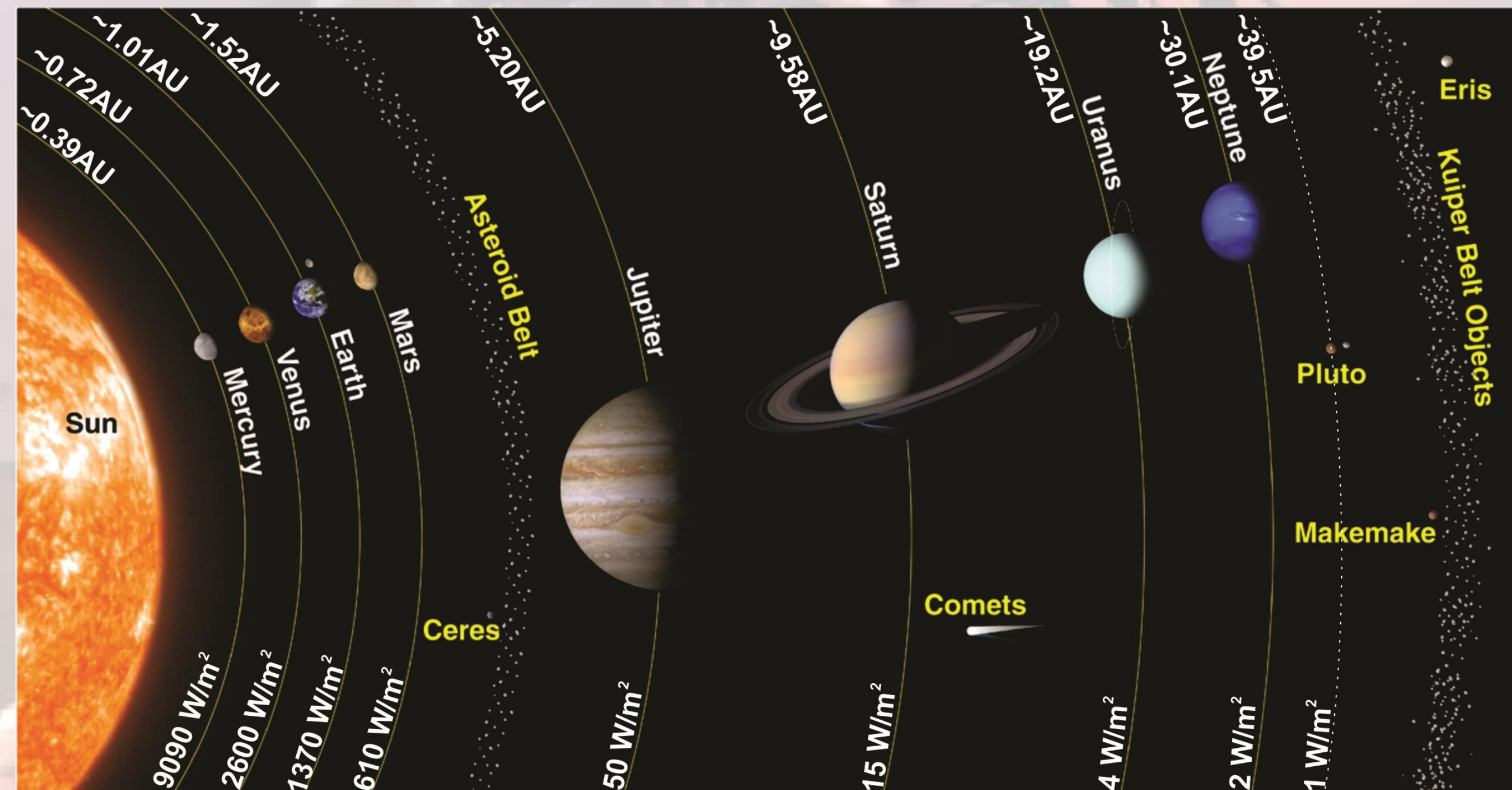
- Europa Clipper orbiter goals are to explore Europa, investigate its habitability and aid in the selection of a landing site for a lander
 - Each flyby would cover a different sector of Europa in order to achieve a medium-quality global topographic survey, including ice thickness
- Europa lies well within the harsh radiation fields surrounding Jupiter, even a radiation-hardened spacecraft in near orbit would be functional for just a few months
 - A wide orbit of Jupiter with several flybys of Europa minimizes radiation exposure and increases data transfer speed
 - Another limiting factor on science for a Europa orbiter is not the time instruments can make observations, but it is the time available to return science data to Earth
- Most instruments can gather data faster than the communications system can transmit it to Earth because of limited number of antennas available to receive the data
 - Between each flyby, the spacecraft would have seven to ten days to transmit data stored during each brief encounter
 - Allows the spacecraft about a year of time to transmit its data compared to just 30 days for an orbiter
 - This results in almost 3X as much data returned to Earth, while reducing exposure to radiation



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MISE Instrument for Planned Europa Clipper Mission

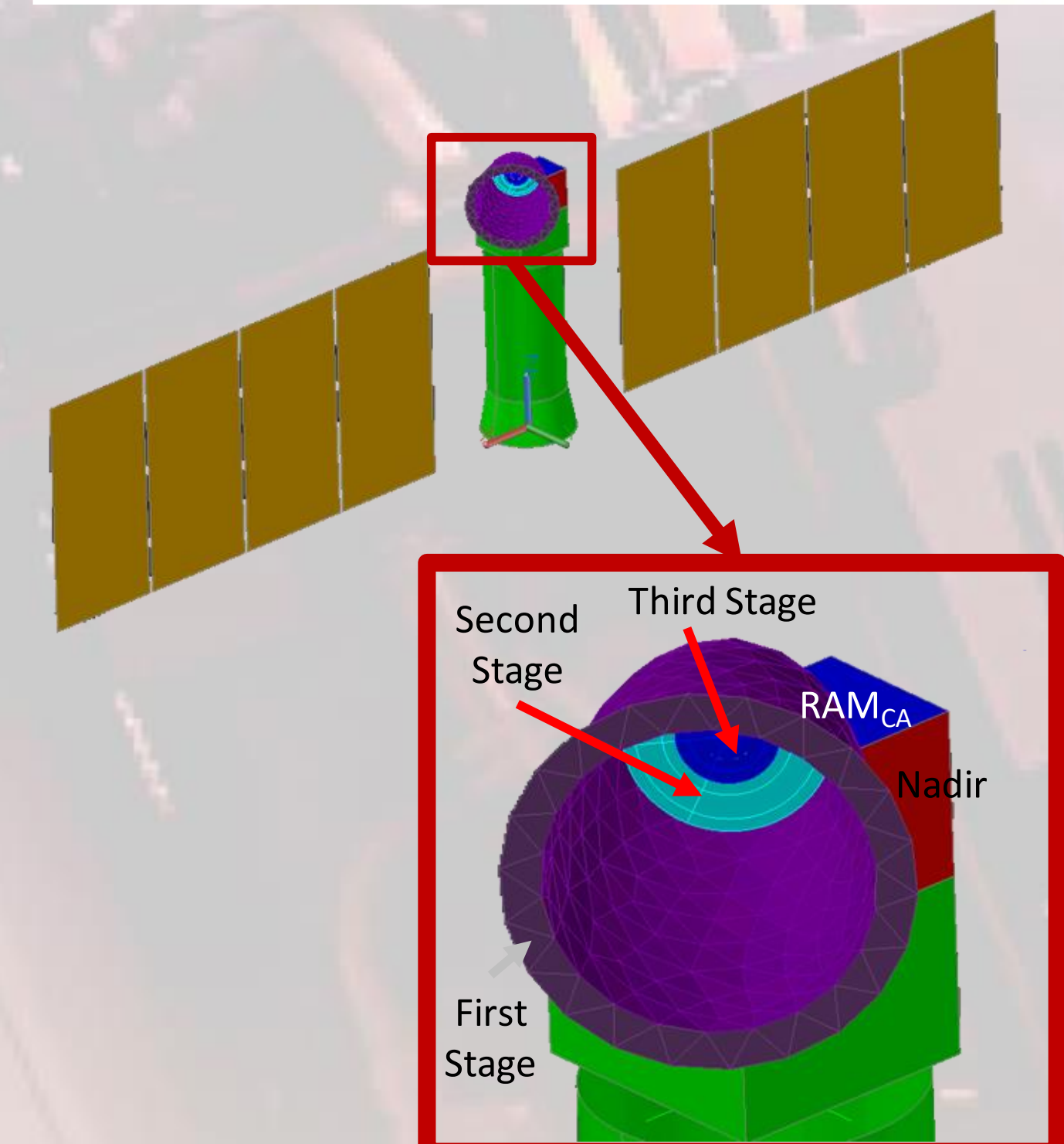
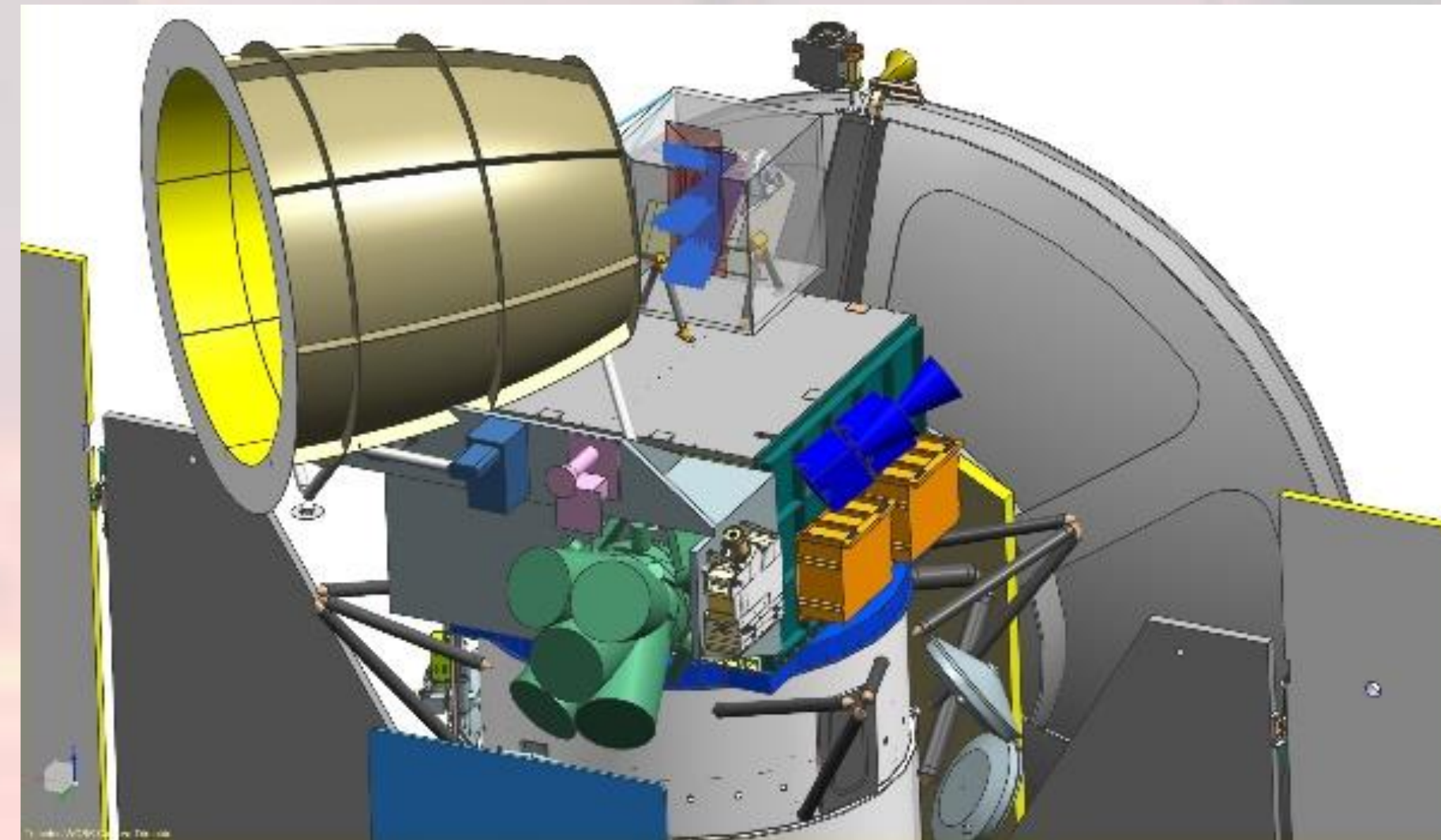
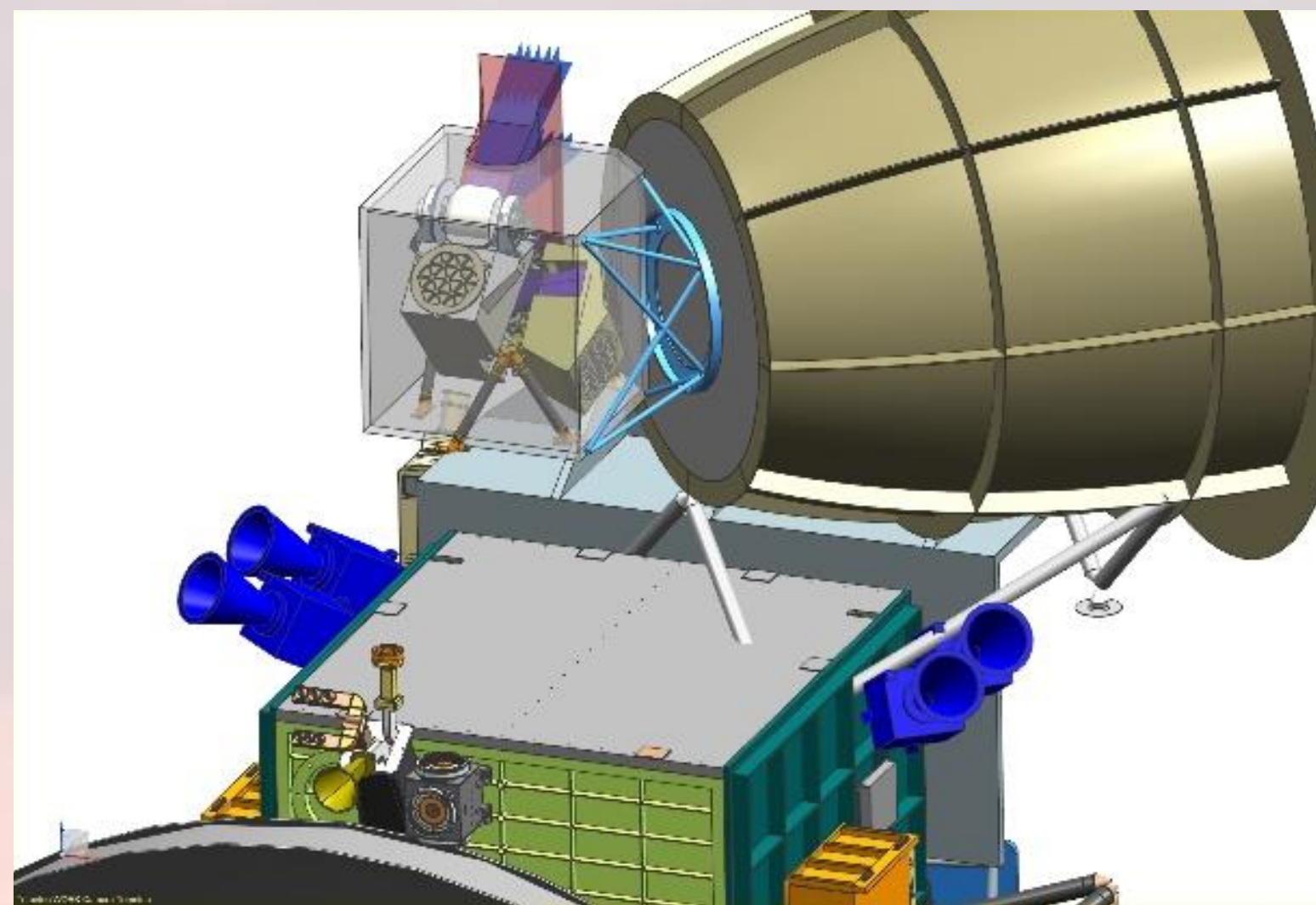
- The Mapping Imaging Spectrometer for Europa (MISE) on the Europa Clipper mission requires cooling to 85 K for the focal plane and 109 K for spectrometer optics
- In project Phase A, trade study was performed to determine if passive cooling was feasible for this application
- Environmental heat sources on the passive cooler come from Europa itself and the Sun
- The IR and albedo contributions from Jupiter are small and can be neglected
- Europa with surface temperature of 102 K and albedo of 0.67 can be significant infrared heat and reflected solar heat source
- Solar flux at Europa varies from 45 to 56 W/m²
- Spacecraft baseline configuration with two-wing solar array limits the possibility of accommodating clear view to cold space for the passive cooler



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MISE Instrument for Europa Clipper Mission (Cont'd)

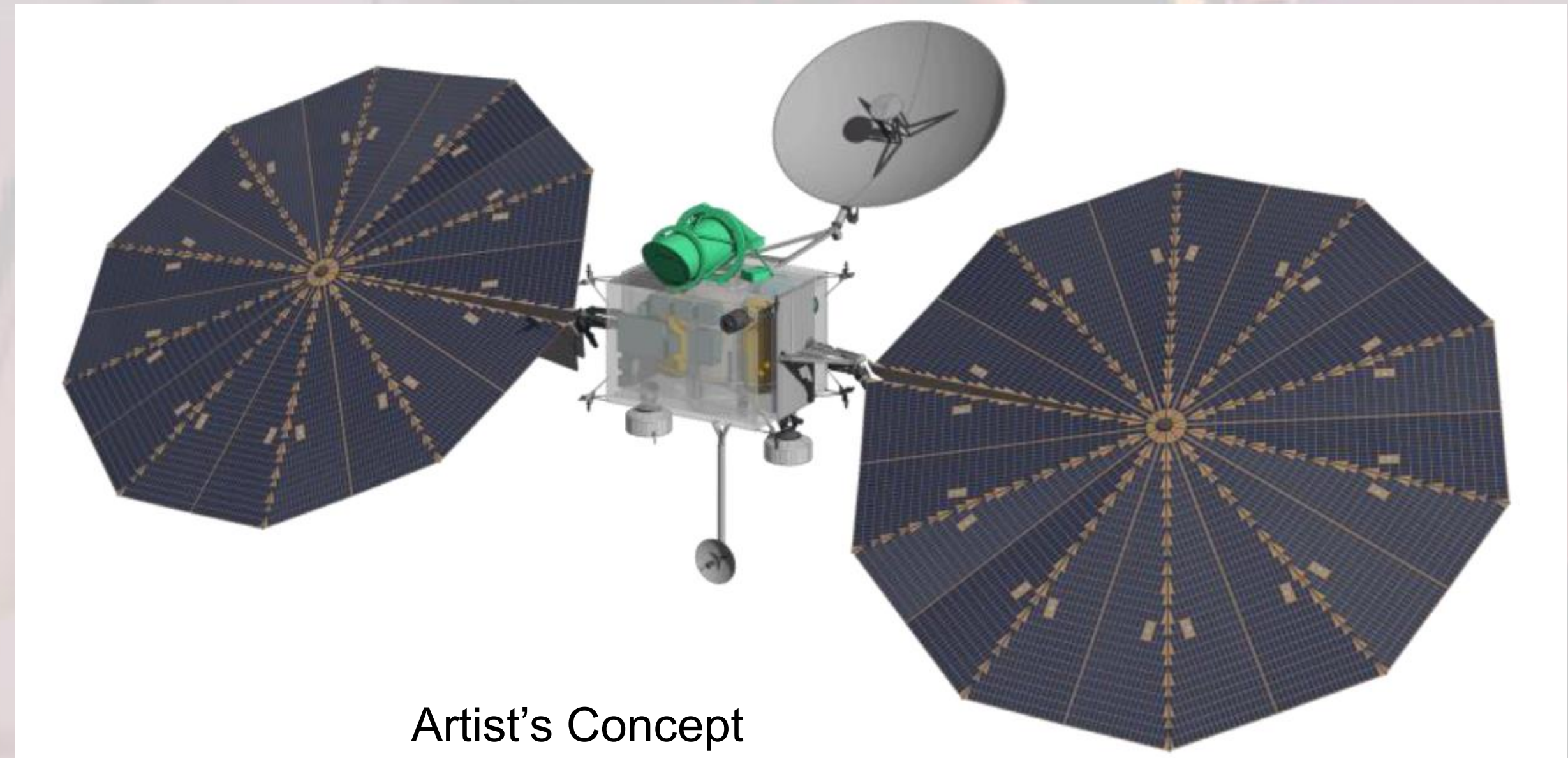
- Successful correlation with agreement to both test conditions to 1K at critical radiator stages
- All correlation changes incorporated into flight models
- MISE instrument with Winston cone passive cooler



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Future Use of Solar Power for Space Applications

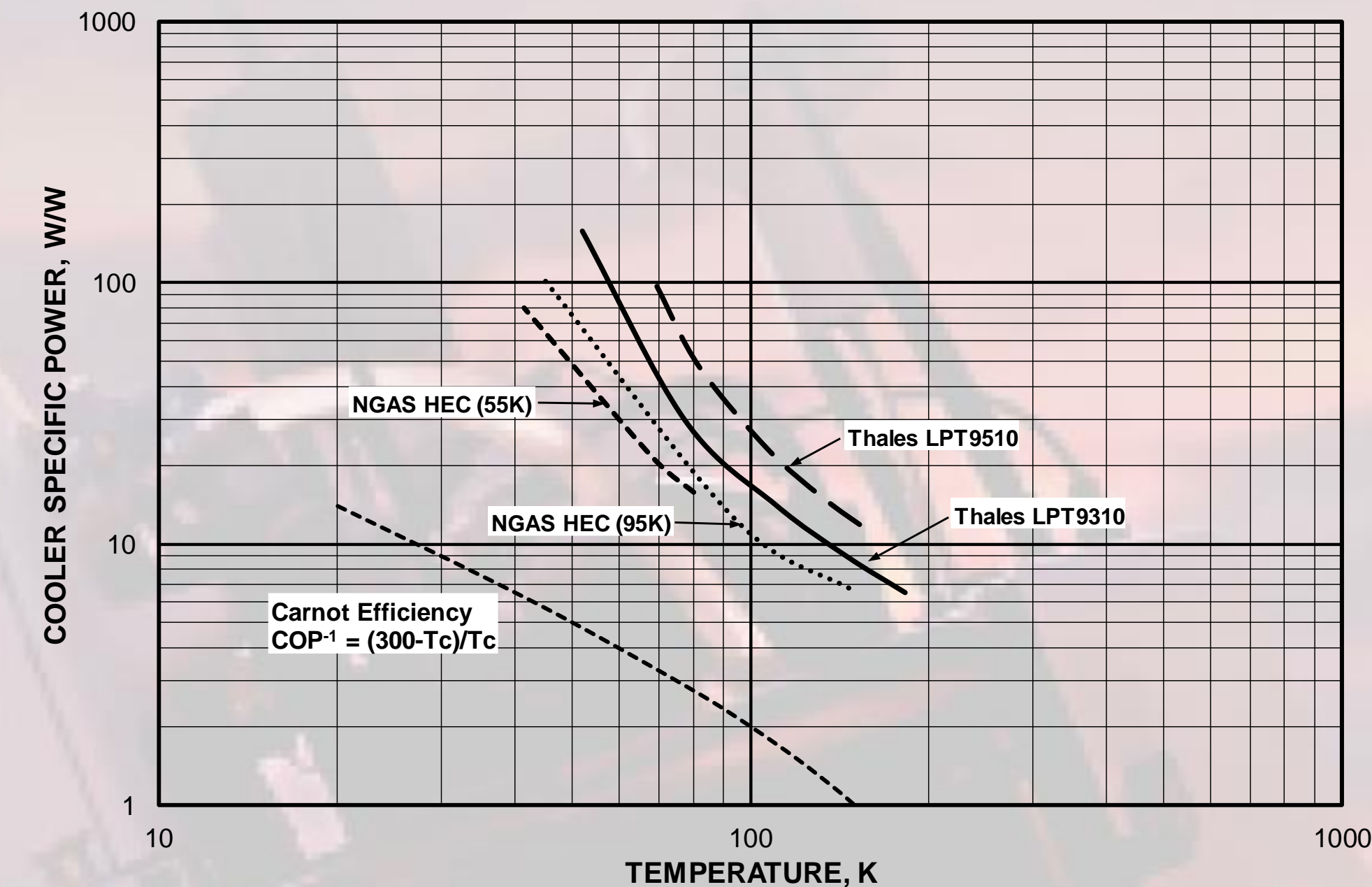
- NASA continues to develop radioisotope power system technology, it also continues to support and fund solar cell technology for future space use
- It is anticipated that solar cell technology will continue to be proposed to power mission concepts bound for the outer solar system
- An example includes NExt Mars Orbiter (NeMO) mission concept planned for launch in early 2020's
 - Moderate size spacecraft with mission lifetime of 6.5 years would require 20 kW solar arrays to power the spacecraft, payload and the NEXT-C ion engines
 - Mars primary mission would be low orbit at 320 km altitude and 75-93 deg inclination with nadir pointing ± 30 deg roll for science observation
 - The large size of the solar arrays that would be required presents a challenge to accommodate instruments requiring cryogenic cooling passively



Artist's Concept

Active Cooling Systems

- Active cooling with mechanical coolers below 100 K is feasible given sufficient power and a room temperature radiator to reject cryocooler and drive electronics waste heat
- Pulse tube (PT) coolers with flexure bearing technology have long successful space flight history with some coolers operating for nearly 15 years without performance degradation
- Oxford cooler technology has gained wider acceptance with low cost tactical cooler manufacturers as a viable option to increase the cooler reliability and life time
- Incorporation of the flexure bearing and the PT technologies, tactical cooler lifetimes have increased tenfold to in excess of 10 years while not appreciably increasing cost
- Thales Cryogenics (Eindhoven, The Netherlands) is one tactical cooler manufacturer that has chosen to invest in this technology and offer a low cost PT cooler
- Plot shows coolers have an order of magnitude lower performance compared to Carnot's efficiency
 - Carnot efficiency calculated in terms of specific power is shown at the bottom of the plot and represents the theoretical maximum performance
 - Cooler input power per watt of cooling (=Specific Power) range is highly dependent on cooler coldtip temperature as shown in the plot
- JPL has been working with Thales Cryogenics for over six years to demonstrate flight worthiness of their PT coolers, as a means to provide low cost, reliable coolers to NASA instruments
- The Tables shows a comparison with cooling at 65K between the SOA and low cost options available from Thales Cryogenics



High Efficiency Cooler (HEC)

4.1 kg
200 WAC (input)
10 in x 4.5in x 12.1 in

Specific power
@ 65 K = 24 WAC/W

(65 K coldtip is required
to cool detector to 70 K
with thermal strap)

Power Input for 1 W of cooling at 65 K = 42 W
Lifetime > 10 years, Total mass= 7.9 kg



Thales LPT9310

7.1 kg
180 WAC (input)
Compressor: 3 in x 8 in
Cold head: 7.5 in x 3 in

Specific power
@ 65 K = 45 WAC/W

(65 K coldtip is required
to cool detector to 70K
with thermal strap)

Power Input for 1.0 W of cooling at 65 K = 54 W
Lifetime > 10 years, Total mass= 8.1 kg

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Summary

- Passive cryogenic cooling below ~ 100 K on outer planetary mission with large solar arrays is challenging given the solar array sun-pointing constraints, payload science pointing requirements and spacecraft communication constraints
- With these constraints and warm solar arrays on two sides of the spacecraft, it is unlikely that clear view to cold space can be found to accommodate radiator with low spacecraft accommodation heat fluxes
- Future outer planetary missions traveling to distances beyond Saturn at 10 AU would require very large solar arrays making extremely difficult to provide a passive cooling solution
- A passive solution, if it exists, is of course the best solution if it does not place undue pointing constraints on the spacecraft attitude for the entire mission
- In these cases, it's likely that active cooling with a mechanical cryocooler will be the only viable option available to instrument designers
- Recent cooler technology advancements over the past 15 years have led to successful applications in Earth missions and a few outer planetary missions
- A cryocooler solution is not without technical issues and requires additional resources including power which may lead to having to increase the size of solar arrays to accommodate the additional power needed
- Heat rejection system with room temperature radiator is needed to reject cooler and electronics waste heat
- Active cooling solution removes requirement of needing clear field of view to cold space; however, it introduces design challenges which need to be addressed including exported vibration, EMI/EMC, and DC/AC magnetic fields

Acknowledgements

- The work described in this presentation and associated paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.